NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

APPLICATION OF AN ENTROPIC APPROACH TO ASSESSING SYSTEMS INTEGRATION

by

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March 2012

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2012	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE Application of an Entropic Approach to Assessing Systems Integration

5. FUNDING NUMBERS

6. AUTHOR(S) Hui Fang Evelyn Tan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943–5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ______N/A______.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

Systems integration is a major endeavor in the development of a system. The goal of integration is to bring separately developed components to create the required system within both the defined schedule and the allocated budget. An entropic approach to assessing the success in attaining the goal, i.e., systems integration success, involves representing the system as a network, whose nodes are the elements of the system and whose links are the connections among the elements, and determining and tracking system network entropy. The work in this thesis considers more than two possible states for each link, explicitly assigning probabilistic measures to systems development and integration activities, and applying it to the integration of a robot used in the detection and destruction of improvised explosive devices. This work demonstrates the feasibility of applying this entropic approach to assessing systems integration success and, specifically, the feasibility of using network entropy as a metric to aid in systems integration.

14. SUBJECT TERMS Network entropy, systems integration assessment, Markov chain, Monte Carlo simulations

15. NUMBER OF PAGES
77

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540–01–280–5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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APPLICATION OF AN ENTROPIC APPROACH TO ASSESSING SYSTEMS INTEGRATION

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
March 2012

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ABSTRACT

Systems integration is a major endeavor in the development of a system. The goal of integration is to bring separately developed components to create the required system within both the defined schedule and the allocated budget. An entropic approach to assessing the success in attaining the goal, i.e., systems integration success, involves representing the system as a network, whose nodes are the elements of the system and whose links are the connections among the elements, and determining and tracking system network entropy. The work in this thesis considers more than two possible states for each link, explicitly assigning probabilistic measures to systems development and integration activities, and applying it to the integration of a robot used in the detection and destruction of improvised explosive devices. This work demonstrates the feasibility of applying this entropic approach to assessing systems integration success and, specifically, the feasibility of using network entropy as a metric to aid in systems integration.

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ACKNOWLEDGMENTS

The author is thankful to her thesis advisor, Dr. Tom Huynh, for his continual guidance, encouragement and patience throughout this thesis. He has provided the author many invaluable lessons, which have helped her develop a deeper understanding of and appreciation for systems integration in general and the use of entropic measures in systems integration in particular.

The author is also grateful to her second reader, Dr. Kim Leng Poh, for taking the time to review this thesis.

Lastly, the author would like to express her heartfelt thanks to her spouse, Ronny Ang, for his support in a number of ways, throughout her study at the Naval Postgraduate School.

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I. INTRODUCTION

Systems integration is a major endeavor in the development of a system. The goal of integration is to bring separately developed elements to create the required system according to a defined schedule without busting an allocated budget. To be able to achieve the goal, unforeseen problems that prevent the desired system from being brought into existence as planned need to be discovered as early as possible. This desire cannot be achieved unless the integration is carried out properly (starting with design and development of the elements of the system), monitored, and assessed during the course of integration.

For a system to be successfully integrated, its elements must not only be successfully connected but also interoperable. Successful connectivity and interoperability between the elements of the system being integrated, hence successful system integration, are related to development and integration activities. As the success of these activities is by no means certain, they can be ascribed a probability measure. It is the probabilistic nature of the systems development and integration activities that motivates the entropic approach to assessing systems integration success espoused in Huynh (2011). This entropic approach involves modeling a system as a network with its nodes being the elements of the system and its links being the connections or couplings between the elements, and using network entropy as an indicator to assess systems integration. The network entropy is the Shannon entropy averaged over all states of the links connecting the elements of the network. During a system integration period, if the system migrates toward higher risk of failed integration, the network entropy of the system will decrease.

The state of a link coupling two elements corresponds to the probability of successfully connecting and testing the elements, and the probability that the elements pass interoperability testing. These probabilities are related to the probabilities of successful development of the elements, which correspond to the different states of successful development of the elements. As a result, a link can have many different

states. In Huynh (2011), only two states are assigned to a link. Subscribing to the entropic approach thus precipitates a need to extend the work in Huynh (2011) to links with many states. The objectives of this thesis are 1) to extend the entropic approach to meet this need and 2), for the purpose of illustration, to demonstrate the resulting extension to the assessment of the success of integrating an IED robot, which is a robot performing the functions of detecting and destroying improvised explosive devices (IED).

A. RESEARCH QUESTIONS

Achieving the objective of the thesis requires answering the following research questions:

1. What does the extension of the entropic approach to links with many states involve?
2. How is the network entropy explicitly used in the assessment of systems integration in general and of the integration of the IED robot in particular?

B. APPROACH

The approach to answering the questions consists of the following steps:

1. Defining states of a link connecting two elements of a system, based on the probability of successful development of each element;
2. Determining the probabilities of successful development of the elements using probabilistic modeling and Monte Carlo simulations;
3. Determining the probability that a link is in each of the states defined in Step 1 – the probability of successfully integrating any two elements of the system as a function of the probabilities of the system development and integration activities;
4. Calculating the network entropy, using the results in Step 3;
5. Applying Steps 1 to 4 to assess the success of integration the IED robot in various integration scenarios.

C. BENEFITS OF RESEARCH

It is envisaged that the proposed entropic approach could be used as an aid to system integrators in tracking the systems integration progress and determining the probability of successful integration. Using this entropic approach to assess systems integration will help system integrators to be aware of the systems integration effort needed in each integration phase so as to be better prepared if corrective actions need to be taken.

D. THESIS STRUCTURE

This thesis is divided into five chapters. Chapter I provides background information and the purpose of this thesis. Chapter II covers literature on systems integration and systems integration success indicators. Chapter III introduces the network entropy and its calculation. This chapter also explains how the results can be used to assess systems integration. Chapter IV demonstrates the use of the proposed entropic approach to assess the integration of the IED robot. Finally, Chapter V covers the conclusion of the thesis and recommendations.

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II. SYSTEMS INTEGRATION AND ASSESSMENT INDICATORS

A. SYSTEM INTEGRATION

Systems integration is a major endeavor in the development of a system. The objective of systems integration is to put separately developed elements together to produce a required system that meets all its performance requirements, within the allocated timeline and budget. "Unforeseen problems" that could prevent the achievement of this objective must be discovered as early as possible (Muller 2011). In addition, the integration has to be carried out in proper order (starting with design and development of the constituting elements), monitored, and assessed during the course of integration (Huynh and Osmundson 2011).

Muller (2011) attributes unforeseen problems to a number of reasons. The first reason is the limited knowledge of the system creation team. When the creation process enters new areas of knowledge, no one has prior encounters with these problems and, hence, no ability to anticipate the occurrence of these problems. The second reason is invalid assumptions. For example, in the initial stage of the design phase, many assumptions are necessarily made to deal with many unknowns (e.g., ambiguous system design requirements). The limited intellectual capability of humans could be the reason behind those invalid assumptions made unknowingly. The third reason is that unforeseen problems are commonly due to "interference between functions or components." For example, two software functions running on the same processor may perform well individually, but, because of cache pollution or memory trashing, they may be way too slow when running concurrently (Muller 2011).

In Huynh and Osmundson (2011), the early realization of unforeseen problems is crucial to the integration of complex systems. The term "complexity" is used in many different ways in the systems domain, dependent on the kind of system being characterized, or perhaps on the disciplinary perspective being brought to bear (Sussman 2002). Moses (2000) and Sussman (2002) define "the complexity of a system simply as the number of interconnections between the parts."

Huynh and Osmundson (2011) consider a complex system to be made up of a large number of elements that interact with each other. These elements, separately developed by different developers, are put together by a systems integrator to form the required system. The average number of elements that are successfully connected reflects the complexity of the system. As the number of elements to be connected increases, the complexity of systems integration also increases. Two elements are considered connected successfully if they pass connection testing upon physically and logically connected.

For a system to be considered successfully integrated, all the elements that make up the system must not only be successfully connected, they would need to be interoperable as well. “Interoperability” is defined as the ability of two or more systems or components to exchange information and to use the information that has been exchanged (IEEE 1990). Two elements are deemed to be interoperable if their interface has passed interface testing and are capable of effectively processing exchanged data and performing procedures. The mean number of connected elements that have passed the interface testing reflects the interoperability of the system (Huynh and Osmundson 2011). Hence, systems integration is dependent on the complexity and interoperability measures of the system. These measures are functions of development and integration activities and their success probabilities. The probabilistic nature of these activities is intrinsic in systems development and integration, giving rise to those unforeseen problems (Huynh and Osmundson 2011).

A number of activities and capabilities are identified to be crucial to the success of systems integration. Excepted from Huynh and Osmundson (2011), these activities and capabilities include the following (Sage 2005):

- Understanding of the requirements and their interrelationships
- Managing complex interfaces between scientific and engineering organizations
- Facilitating infusion of advanced technology from many sources
- Independently assessing technical performance
- Exercising project management experience and discipline

- Implementing effective technology management and a transition process for risk reduction
- Conducting timely trade studies to define system architectures that minimize cost and risk
- Designing an architecture conducive to integration feasibility
- Developing and testing the functioning individual subsystems of the system
- Successfully developing and testing the interfaces between and among the individual systems of the system
- Independently certifying compliance with the system architecture and timely
- Accurately assessing risk and executing an agreed-to plan and a process for testing, based on a risk assessment
- Defining accurate operational requirements
- Exercising a full spectrum of the subsystem activities (end-to-end) by subsystem developers
- Implementing certain common processes and infrastructure in the system integration environment promoting effectiveness and efficiencies
- Disseminating information pertinent to each integration event, such as test status, equipment availability, and results

These activities and capabilities can be ascribed a probabilistic measure, as the successes of these activities and capabilities are not certain (Huynh and Osmundson 2011). It is the probabilistic nature of the systems development and integration activities and capabilities that motivates the consideration of using indicators as measures of systems integration success (or failure).

B. SYSTEMS ASSESSMENT INDICATORS

Entropy or entropy-based metrics have been used in many different areas, such as population dynamics and stability, engineering, medicine, management economics, etc., In risk management of virtual enterprise, an entropy weight matter-element assessment model is used to assess virtual enterprise risk (Xiu and Qi 2007). In the arena of medical diagnosis and prognosis, a maximum entropy network is employed to assess auxiliary lymph node metastases in early breast cancer patients (Choong et al. 1994). In

engineering project management, a fuzzy entropy weight is applied in assessing risk of an engineering project (Wu et al. 2009). In Wu and Jonckheere (1992), a mutual Kolmogorov-Sinai entropy approach is used for nonlinear estimation. In Demetrius and Manke (2005), a network entropy, a Kolmogorov-Sinai invariant, is used to establish that the evolutionarily stable states of evolved biological and technological networks are characterized by extremal values of network entropy.

In Dong et al. (2009), a maximum entropy approach is considered for the prediction of road traffic state. Traffic state prediction is useful as it provides travellers with future traffic information, which helps them make informed decisions on the fastest route to get to their destinations. Dong et al. (2009) categorize the prediction problem as a classification problem and apply the maximum entropy approach to model the prediction process. The application of the maximum entropy method is illustrated with a day's traffic data in Beijing. The results show that it is feasible to employ the maximum entropy model for traffic state prediction.

In Sakalauskas and Kriksciuniene (2011), the ability to forecast the long-term trend changes for stock prices and market index is explored. This ability is realized through the integration of two econometrical measures of information efficiency – Shannon entropy and Hurst exponent. Shannon entropy (which is explained in Chapter III) can be applied to evaluate long-term correlation of time series, while Hurst exponent can be applied to classify the time series in accordance to existence of trend. Hurst exponent is the statistical measure of time series long-range dependence, and its value falls in the interval [0, 1] – a value in (0.5, 1] indicates that the time series is persistent and the value will stay high in nearest future; a value in [0, 0.5) indicates that the time series anti-persistent and the value will switched between high and low values in the long-term. An aggregated entropy-based indicator combining Shannon entropy and Hurst exponent then predicts the trend turning point of financial time series. A database, which consists of daily stock index values for duration of more than five years, is used to illustrate the feasibility of the approach. The results show that this entropy approach can be used as an aid for long-term investors to predict strategy changes.

In Ridolfi et al. (2011), an entropy approach is used to assess the maximum non-redundant information content that can be obtained by an urban rainfall network for different sampling intervals. The rainfall network of Rome is used as an example to illustrate the assessment. The rainfall records are categorized for different seasons and different sampling time intervals. The results show that the maximum non-redundant information values and the corresponding sampling intervals have a linear relationship on a semi-log curve.

Examples of network entropy application include Huynh (2010) and Huynh (2011), which, respectively, use network entropy as a metric for SoS or network safety assessment and system integration assessment. On the one hand, in Huynh (2010), a system is modeled as a network and the concept of nodal similarity is employed. Two nodes are said to be similar if they are connected and interoperable with each other. They are deemed dissimilar if their connectivity and/or interoperability are undesirably affected by, for example, operational and environmental causes. On the other hand, in Huynh (2011), a system is modeled as a network and the concept of link similarity is employed. The link between two elements is considered similar if they are integrated successfully and dissimilar if they fail to integrate. The connection between nodal or link similarity and system integration state is established with help of the Similarity Principle, enunciated in Lin (2008) for a mixture of chemical species. According to the Similarity Principle, "If all the other conditions remain constant, the higher the similarity among the components is, the higher value of entropy of the mixture (for fluid phases) or the assemblage (for a static structure of a system of condensed phases) or any other structure (such as chemical bond or quantum states in quantum mechanics) will be, the more stable the mixture or the assemblage will be, and the more spontaneous the process leading to such a mixture or an assemblage or a chemical bond will be." The state of maximal similarity (or indistinguishability) thus corresponds to the state of maximal entropy (Lin 2008). A similarity principle for a system (or an SoS) can be analogously stated: "The higher the similarity among the links of a system (systems of an SoS) is, the higher the value of the entropy of the system (SoS) will be, and the more stable the system (SoS) will be." Finally, it is the work in Huynh (2011) that inspires the work in this thesis.

C. ENTROPIC APPROACH TO SYSTEMS INTEGRATION ASSESSMENT

Consider a network of N elements which interact with each other through L number of links connecting them. Let H be the Shannon entropy averaged over all stationary states (Shannon 1948). It is defined as follows:

$$H = -\sum_{l=1}^{L}\sum_{k=1}^{M} p_{lk} \ln p_{lk} \tag{1}$$

in which M is the number of possible states of each link, p_{lk} is the probability that the l^{th} link is in state k, with $\sum_{k=1}^{M} p_{lk} = 1$, and L is the total number of links in the network.

The risk growth rate of the network, ρ, is defined in Huynh (2010) as follows:

$$\rho := \lim_{t\to\infty}\left\{-\frac{1}{t}\ln\left[1-P_{\varepsilon}(t)\right]\right\} \tag{2}$$

in which $P_{\varepsilon}(t)$ is the probability that the mean number of similar links at time t deviates by more than ε from the number of similar links for successful systems integration (Huynh 2010; Demetrius, Gundlach and Ochs 2004; Demetrius and Manke 2005). Such deviations suggest risk of failed systems integration, and the rate of change of the deviations indicates the rate of risk growth.

Huynh (2010) establishes the relationship that increasing rate of risk growth corresponds to decreasing entropy,

$$\Delta H \cdot \Delta\rho < 0, \tag{3}$$

in which $\Delta\rho$ describes change in ρ and ΔH describes change in H.

During a stage of the systems integration phase, if the links migrate toward dissimilarity, the system migrates toward higher risk of failed integration and its network entropy decreases. Hence, using this relationship, network entropy can be used as an indicator to assess systems integration success. The calculation of the network entropy is discussed in detail in Chapter III.

In Huynh (2011), the link between two elements is considered similar if they are integrated successfully and dissimilar if they fail to integrate. Each link is assumed to take two possible states: 0 for similar (success) and 1 for dissimilar (failure) and the Shannon entropy in (1) becomes

$$H = -\sum_{l=1}^{L}\left[p_{l0} \ln \frac{p_{l0}}{1-p_{l0}} + \ln(1-p_{l0}) \right] \tag{4}$$

where $l0$ means the two nodes linked by l are successfully integrated and p_{l0} is dependent on the probabilities of successful designing and development of the elements connected by l.

To assess p_{l0}, the probability of successful connecting and testing the pair of elements linked by l and the probability that the pair of elements passes interoperability testing need to be determined. These probabilities for all the links in the system would need to be estimated in order to use the Shannon entropy as a metric to monitor systems integration.

Again, as explained in Chapter I, this thesis extends this entropic approach by considering links with more than two states and assigning probabilistic measures to the systems development and integration activities and capabilities in order to obtain the probabilities required in the computation of the Shannon entropy of the system.

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III. NETWORK ENTROPY AND ITS CALCULATION

The purpose of this chapter is to explain the calculation of network entropy and its use in assessing systems integration success. Section A lists the flow of top-level systems development and integration activities and describes the probabilistic nature of these activities. Section B explains the computation of the network entropy. Lastly, Section C describes the determination of the network entropy in different phases of systems integration.

A. PROBABILISTIC NATURE OF DEVELOPMENT AND INTEGRATION ACTIVITIES

For a system to be successfully integrated, its elements must not only be successfully connected but also interoperable. Successful connectivity and interoperability between the elements of the system being integrated, hence successful system integration, are related to both development and integration activities. Only top-level system development and integration activities are considered in this thesis. They consist of designing (D), building (B) and testing (T_1) the elements of the system. Integration activities include connecting the elements (C) (e.g., pairwise), connection testing (T_2) and interoperability testing (T_3). These development and integration activities are shown in Figure 1, outlined by the red dashed lines. Figure 1 also shows the flow of the activities, indicated by the blue solid (for successive transition if no failures occur) and dashed (for feedback in the event the particular activity fails) arrows. The connectivity among the activities implies that the success or failure of one activity could impact the others. During the element development phase, for example, if the design of element i is poor, even if it were built successfully according to the design, the testing at T_1 (or T_2 or T_3) could still fail.

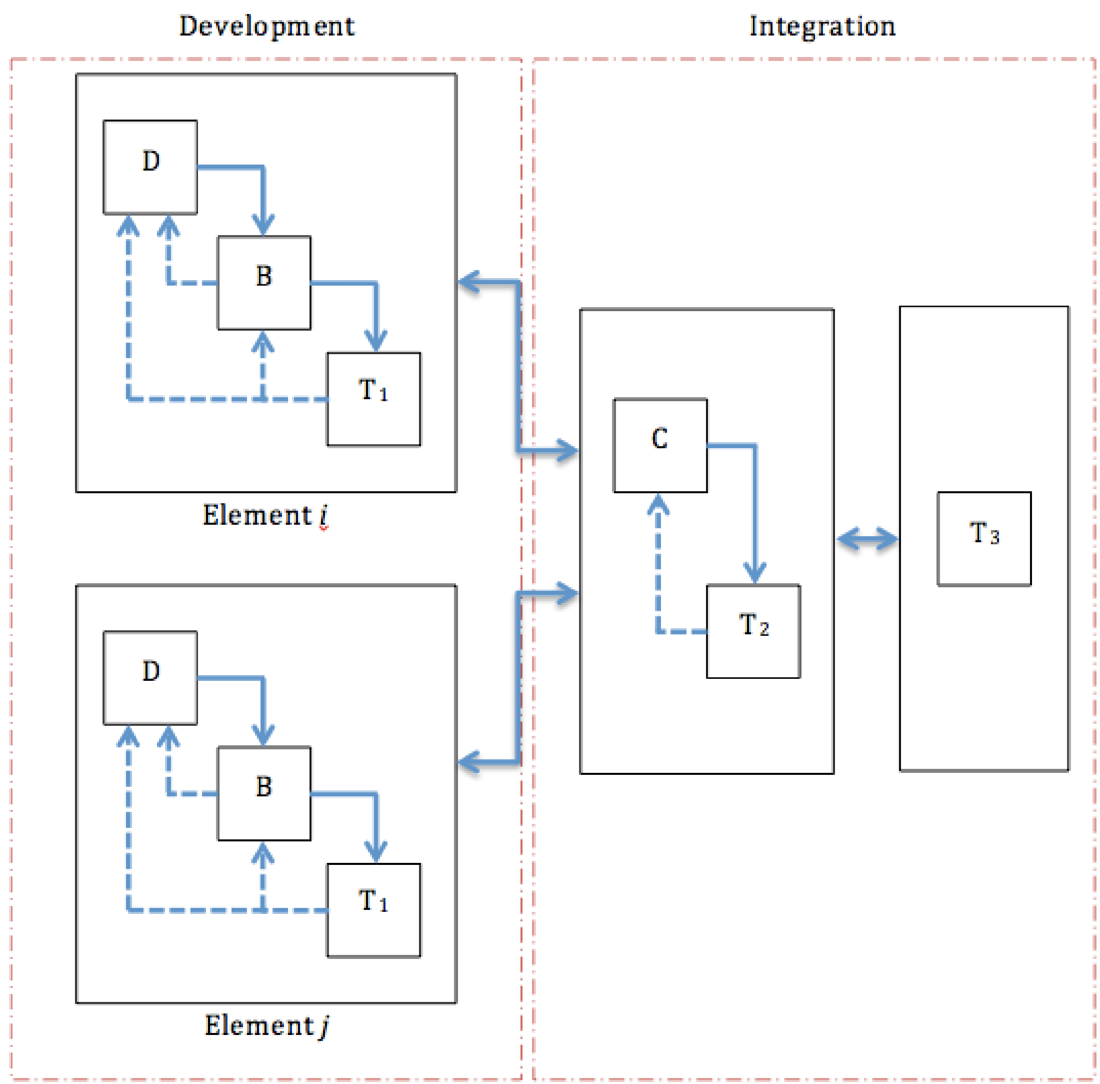

Figure 1. Development and Integration Activities

Again, as the success of the systems development and integration activities is by no means certain, these activities can be ascribed a probability measure (Huynh 2010). Considering the probabilistic nature of the systems development and integration activities, the network entropy could be employed as an indicator to measure systems integration success (or failure). This indicator is the Shannon entropy averaged over all stationary states of the links connecting the elements of the system.

B. ENTROPY METRIC

This section describes the link similarity concept, its relation to network entropy, and the determination of the network entropy.

1. Link Similarity in a Network

As mentioned in Chapter I, Huynh (2011) models a system as a network, employs the concept of similar links in a network, and computes the Shannon entropy of the network based on the link similarity. The link between two elements in the system is considered similar when the elements are successfully connected and are interoperable. These elements are presumed to have been successfully developed (i.e., successfully designed and built according to their performance specifications and interoperability requirements). The link between two elements in the system is considered dissimilar if any factor (design or/and integration) undesirably affects the required performance of the elements coupled by the link, their connectivity, and their interoperability. The link similarity is associated with the integration state of a system or a network and with its entropy.

A system is considered to be in a similar state if the links in the system are similar. It is deemed to be in a dissimilar state if not all the links in the system are similar. When a system has achieved a state in which there is no risk of being dissimilar, the system is considered to be successfully integrated. When a system is in a state in which it is subjected to a risk of being dissimilar, it is very probable that the systems integration would fail. Hence, during systems integration, it is critical to detect the failed-integration states early so that measures can be taken to prevent the occurrence of the impending failed-integration states. Detectors to discover the failed-integration states need not be physical. Network entropy can be used as such detectors.

2. Network Entropy

The network entropy is the Shannon entropy H, averaged over all states as shown in (1). For a system with N elements (i.e., a network with N nodes), the

maximum possible number of links is $\frac{N(N-1)}{2}$, which is obtained only when all the elements interface with each other. Since not all systems have fully connected elements, not all systems have the maximum possible number of links. In Huynh (2011), each link assumes only two possible states. In this thesis, the number of states a link can have is greater than two, i.e., $M > 2$.

a. Link State Categorization

The development of each element of the system involves designing, building, and testing of the element. The probability of successful development, p_D, of an element is thus related to the probability of successfully designing, building, and testing the element. The state of the development of a system can be defined according to the values of the probability of successful element development, p_D. In this thesis, as defined and shown in Table 1, three successful element development states are: “Low” if $0 \le p_D < X_{Low}$, “Medium” if $X_{Low} \le p_D < X_{Med}$, and “High” if $X_{Med} \le p_D \le 1$. The values of X_{Low} and X_{Med} are arbitrarily selected.

Table 1. Successful Element Development States and Probabilities

Element Development State	**Probability of Successful Development, p_D**
Low (L_{ow})	$0 \le p_D < X_{Low}$
Medium (M_{ed})	$X_{Low} \le p_D < X_{Med}$
High (H_{igh})	$X_{Med} \le p_D \le 1$

The state of the link between two elements being integrated depends on the development states of the elements. Since each element can be assigned three different development states, the link can be found in 3^2 possible states, i.e., k takes the

values of 1 to 9. The assignment of one of the nine states to a link is shown in Table 2. Link state 2, for example, results from integrating an element in the development state L_{ow} with another element in the development state M_{ed}.

Table 2. Link States Assignment

		Element j		
		State L_{ow} ($0 \le p_D < X_{Low}$)	State M_{ed} ($X_{Low} \le p_D < X_{Med}$)	State H_{igh} ($X_{Med} \le p_D \le 1$)
Element i	State L_{ow} ($0 \le p_D < X_{Low}$)	State 1	State 2	State 3
	State M_{ed} ($X_{Low} \le p_D < X_{Med}$)	State 4	State 5	State 6
	State H_{igh} ($X_{Med} \le p_D \le 1$)	State 7	State 8	State 9

b. p_{lk} Determination

The probability of a link resulting from integrating two elements of the system is a function of the probability measures of the system development and integration activities. The assessment of systems integration requires the determination of both the probability of successful development of the system elements and the probability of successfully integrating the elements.

(i) *Probability of successful element development*. In this thesis, the probability of successful development of an element is not explicitly determined in terms of the probabilistic measures of the development activities (D, B and T_1 as shown in Figure 1). If the successful development state of an element is assumed to be in one of the three successful element development states, L_{ow}, M_{ed}, and H_{igh}, then the probability of successful development, p_{D_i}, of element i is obtained by generating a

uniformly distributed random number that falls within the range corresponding to an assumed state. For example, the probability that the successful development of element i is in the M_{ed} state is determined by drawing a number from a continuous uniform distribution between X_{Low} and X_{Med}; that is, $p_{D_i} \sim U(X_{Low}, X_{Med})$.

(ii) *Probability of successful pairwise integration*. From Figure 1, the integration of a pair of elements of a system involves connecting (C), connection testing (T_2) and interoperability testing (T_3) of the pair of elements. Hereinafter, connectivity testing refers to connecting the elements (C) and testing their connection (T_2). The probability of successful connectivity of two elements is thus the probability of successfully connecting the elements and testing their connection.

The probability of successful integration of a pair of elements is related to the probabilities of successfully connecting the two elements, and testing the connection and interoperability of the elements. Hence, to obtain the probability of successful integration of a pair of elements of the system, the probabilities of successfully connecting the two elements and passing the connection testing, as well as the probability of the two elements passing the interoperability testing, need to be determined.

(a) *Connectivity Measure*. The success of connecting (C) and testing (T_2) every pair of elements successfully during integration is subject to uncertainty. Even if the developers considered the elements to be developed successfully, success in connecting them and testing their connection during integration would not be certain. Such uncertainty is related to the probabilistic nature of the systems development and integration activities and capabilities (Huynh 2011). In this thesis, the probability of successful connectivity of two elements is assumed to be related to the probability of successful development activities and is determined based on the probabilities of successful development of the two elements to be connected.

Let $p_C(i, j)$ denote the probability of successful connectivity of elements i and j. Since the probability of successful connectivity of elements i and j would be unlikely to exceed the probability of successful development of either element and since the element in a less successful development state would

adversely affect the pairwise integration, $p_C(i,j)$ is taken to be the minimum of p_{D_i} and p_{D_j} (i.e., $p_C(i,j) = \min(p_{D_i}, p_{D_j})$).

To determine the value of $p_C(i,j)$, the values of p_{D_i} and p_{D_j} would thus need to be obtained. As mentioned earlier, p_{D_i} is obtained by generating a uniformly distributed random number that falls within the range corresponding to an assumed state. This is likewise for p_{D_j}. Furthermore, since the probabilities of successful development activities cannot be assessed by a single probability value, a range of possible values, instead of a single estimate, is studied. Monte Carlo simulations are carried out to generate these probabilities of successful element development. Using Monte Carlo simulations, the probability of successful connectivity of elements i and j, $p_C(i,j)$, is computed according to

$$p_C(i,j) = \frac{1}{R}\sum_{r=1}^{R}\min(p_{D_i}, p_{D_j}) \tag{5}$$

in which R is the number of simulation runs, p_{D_i} and p_{D_j} are the probabilities of successful development of elements i and j, respectively.

(b) *Interoperability Measure*. The probability of two elements of the system passing the interoperability testing (T_3) during integration is also subject to uncertainty. The success of interoperability testing of the two elements is not certain even if the developers deemed the elements to have been developed successfully. Again, such uncertainty is related to the probabilistic nature of the systems development and integration activities and capabilities (Huynh 2010; Huynh 2011). The probability of two elements being successfully interoperable is assumed to be based on the probability of successful development of the two elements to be tested for interoperability. This assumption is the same assumption used in the determination of probability of successfully connecting them and passing the connection testing.

Let $p_I(i,j)$ denote the probability of successful interoperability between elements i and j. As in the computation of $p_C(i,j)$, $p_I(i,j)$ is taken to be the minimum of p_{D_i} and p_{D_j}, i.e., $p_I(i,j) = \min(p_{D_i}, p_{D_j})$. Using Monte Carlo simulations, the probability of successful interoperability between elements i and j, $p_I(i,j)$, is computed according to

$$p_I(i,j) = \frac{1}{R}\sum_{r=1}^{R} \min(p_{D_i}, p_{D_j}) \tag{6}$$

in which R is the number of simulation runs, p_{D_i} and p_{D_j} are the probabilities of successful development of elements i and j, respectively.

(c) *Combining Connectivity and Interoperability Measures*. Even if the physical and logical connections between two elements pass the connectivity testing and each element is able to send and receive data from each other, the interoperability testing may still fail if, for example, the software embedded in the element is not designed to or fails to use the received information. The integration of two elements, again, involves connecting them and testing their connection and, having established their successful connectivity, testing their interoperability. A connectivity state is defined as the state in which two elements are successfully connected and pass connection testing; and, by construction, there are nine connectivity states. Likewise, an interoperability state is defined as the state in which two elements, whose successful connectivity has already been established, pass interoperability testing; and, by construction, there are also nine interoperability states. An integration state of the two elements corresponds to both a connectivity state and an interoperability state of the elements. If the integration state is k, where $k = 1,...,9$, then both the connectivity state and interoperability state must necessarily be k. That is, if link (i,j) – resulting from the integration – is in state k, it is necessary that both elements i and j be in the k^{th} connectivity and interoperability states, respectively, denoted by i_k and j_k. It then follows that $p_C(i,j)$ and $p_I(i,j)$ can be written as $p_C(i_k, j_k)$ and $p_I(i_k, j_k)$, respectively.

In this thesis, the event of establishing the connectivity testing (C and T_2) and the event of passing the interoperability testing (T_3) are assumed to be independent. With this assumption, the probability, $p_k(i,j)$, of successfully integrating elements i and j of the system or of finding the link (i,j) coupling the two elements in state k is determined from

$$p_k(i,j) = p_C\left(i_k, j_k\right) p_I(i_k, j_k) \tag{7}$$

Note that the index l in the definition of the network entropy in Section B.2 corresponds to (i,j), where $i,j = 1,\ldots,N$. For example, as will be seen in Chapter IV, $l=1$ corresponds to $(1,2)$, $l=2$ to $(1,3)$, etc., Consequently, in the definition of the network entropy, p_{lk} is $p_k(i,j)$, where the value of l corresponds appropriately the values of i and j in the link (i,j).

C. NETWORK ENTROPY AND SYSTEMS INTEGRATION SUCCESS

As mentioned in Section B in this chapter, a system is considered to be successfully integrated when the system has achieved a state in which there is no risk of the links in the system being dissimilar. If the links in the system migrate toward higher risk of being dissimilar, i.e., failed integration, the network entropy of the system will decrease. To track the progress of the overall systems integration, the network entropy of the system should be monitored during specified systems integration periods. Since the systems integration success depends on the development success of the system elements, it is important to track the state of the element development (i.e., L_{ow}, M_{ed} and H_{igh}).

As the systems integration progresses, it is possible that the design of an element of the system, for example, is improved. This would result in a change in the development state of the element, as well as the range of the probability of successful development (i.e., values of X_{Low} and X_{Med}). A Markov chain (Klimov 1986) is employed in this thesis to account for these random changes in the element development

state and probability range. A Markov chain is suitably applied because the next state of the element development depends on the present state and not on the preceding states.

Let P be a finite $n \times n$ transition matrix of a Markov chain, $P := \left[\pi_{xy} \right]$ in which π_{xy} is the transition probability of going from state x to state y. In this case, since there are three states of successful element development (L_{ow}, M_{ed} and H_{igh}), $n = 3$ and $x, y = L_{ow}, M_{ed}, H_{igh}$. Hence,

$$P = \begin{pmatrix} \pi_{L_{ow}L_{ow}} & \pi_{L_{ow}M_{ed}} & \pi_{L_{ow}H_{igh}} \\ \pi_{M_{ed}L_{ow}} & \pi_{M_{ed}M_{ed}} & \pi_{M_{ed}H_{igh}} \\ \pi_{H_{igh}L_{ow}} & \pi_{H_{igh}M_{ed}} & \pi_{H_{igh}H_{igh}} \end{pmatrix} \tag{8}$$

in which the $\sum \pi_{xy} = 1$ for any row in the matrix.

Figure 2 shows a transition diagram that includes the three successful element development states and the respective state transition probabilities. An element currently in the development state M_{ed} could transition to three possible states. The three solid (pink) arrows indicate the three possible transitions. The element could go to the development state L_{ow} or H_{igh}, or remain in the current development state M_{ed} with probabilities $\pi_{M_{ed}L_{ow}}$, $\pi_{M_{ed}H_{igh}}$, and $\pi_{M_{ed}M_{ed}}$, respectively. Transitions of this kind also apply to an element in the development states L_{ow} and H_{igh}. The possible transitions for development states L_{ow} and H_{igh} are shown by dot-dashed (blue) and dashed (green) arrows, respectively, with the corresponding transition probabilities shown with the arrows.

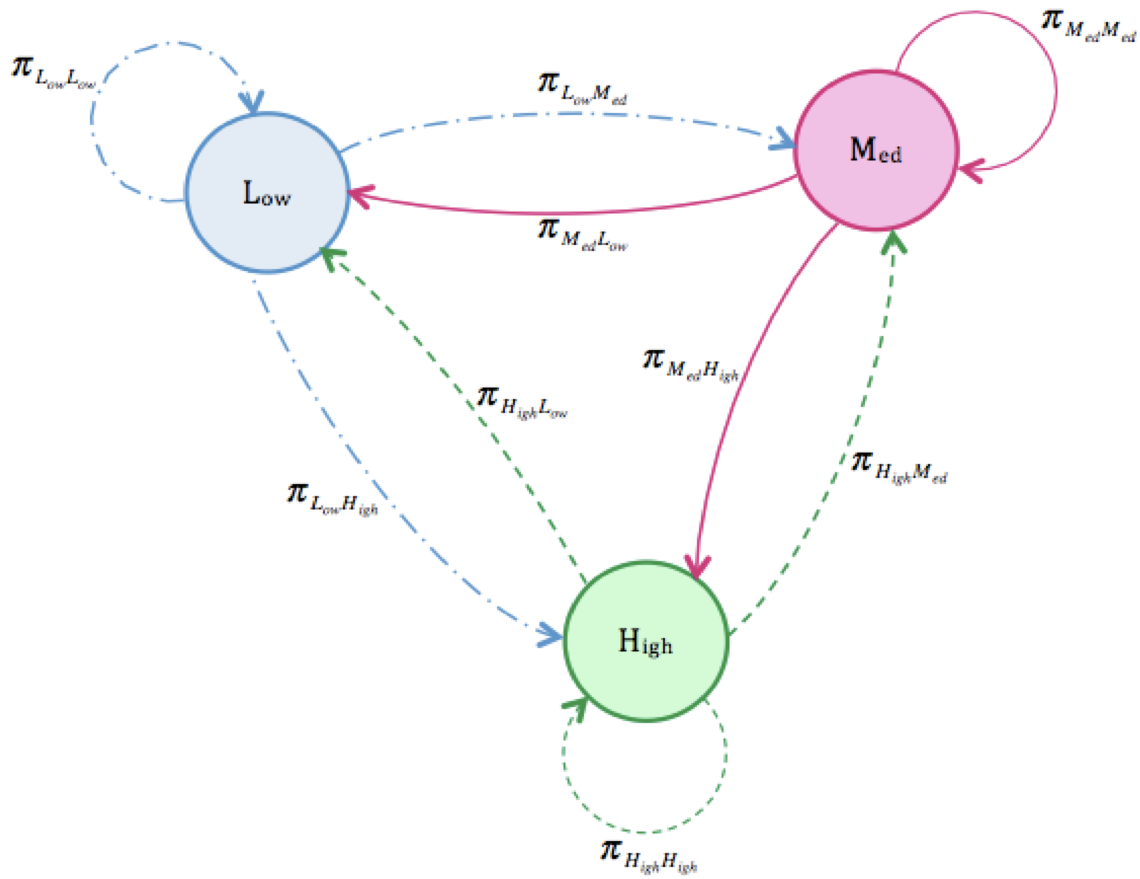

Figure 2. State Transition Diagram

Let x be a column vector whose three entries are the upper limits of the probability ranges specified in Table 16 for the three element development states L_{ow}, M_{ed} and H_{igh}, $x := \begin{pmatrix} X_{Low} \\ X_{Med} \\ 1 \end{pmatrix}$. The values of X_{Low} and X_{Med}, after a transition period of time $[t, t+\delta t]$, are computed according to

$$x(t+\delta t) = Px(t) \tag{9}$$

These values, X_{Low} and X_{Med}, at $(t+\delta t)$ are used to generate the new probability of successful development of the affected element i, p_{D_i} at $(t+\delta t)$. For example, p_{D_i} at $(t+\delta t)$ of element i in the M_{ed} state is now a number drawn from a continuous uniform distribution between X_{Low} and X_{Med} at $(t+\delta t)$; that is, $p_{D_i} \sim U(X_{Low}, X_{Med})$ at $(t+\delta t)$ and is used to compute the network entropy of the system during the transition period $[t, t+\delta t]$.

The use of a Markov chain to find the updated values of X_{Low} and X_{Med} at $(t+\delta t)$ is applicable to scenarios in which there are improvements made to the element development. In these scenarios, the transition matrix reflects the improvements, and as a result, X_{Low} and X_{Med} at $(t+\delta t)$ will become larger than X_{Low} and X_{Med} at t. For cases in which problems (e.g., technology limitations) during the transition period $[t, t+\delta t]$ hinder the successful development of the element, the values of X_{Low} and X_{Med} at $(t+\delta t)$ will be decreased.

IV. ASSESSMENT OF IED ROBOT INTEGRATION SUCCESS

It is of interest to use a robot to engage an improvised explosive device (IED) by searching for, detecting, and destroying it. The development of the IED robot involves integrating its elements or components. This chapter illustrates the application of the entropic approach to assessing its integration.

A. IED ROBOT

To apply the network entropy to assess systems integration success, the system is represented as a network. The IED robot, which is a system, is modeled as a network, in which the elements that form the system are considered as its nodes and the interfaces between the elements are considered as the links that join the elements. Again, the main purpose of the IED robot is to destroy IEDs. To achieve this purpose, the robot must carry out the functions shown in Figure 3. The functional decomposition captured in Figure 3 indicates that, to carry out the function "Destroy IEDs," the IED robot must be able to perform these functions: "Provide Power," "Process," "Communicate," "Move," "Sense," and "Shoot." The function "Move" is, in turn, supported by "Advance," "Reverse," "Turn," and "Stop." The function "Sense" is supported by "Scan" and "Detect." The IED robot must thus be able to power its elements, process and communicate internal commands, move and scan in search of IEDs, detect them, and finally shoot them.

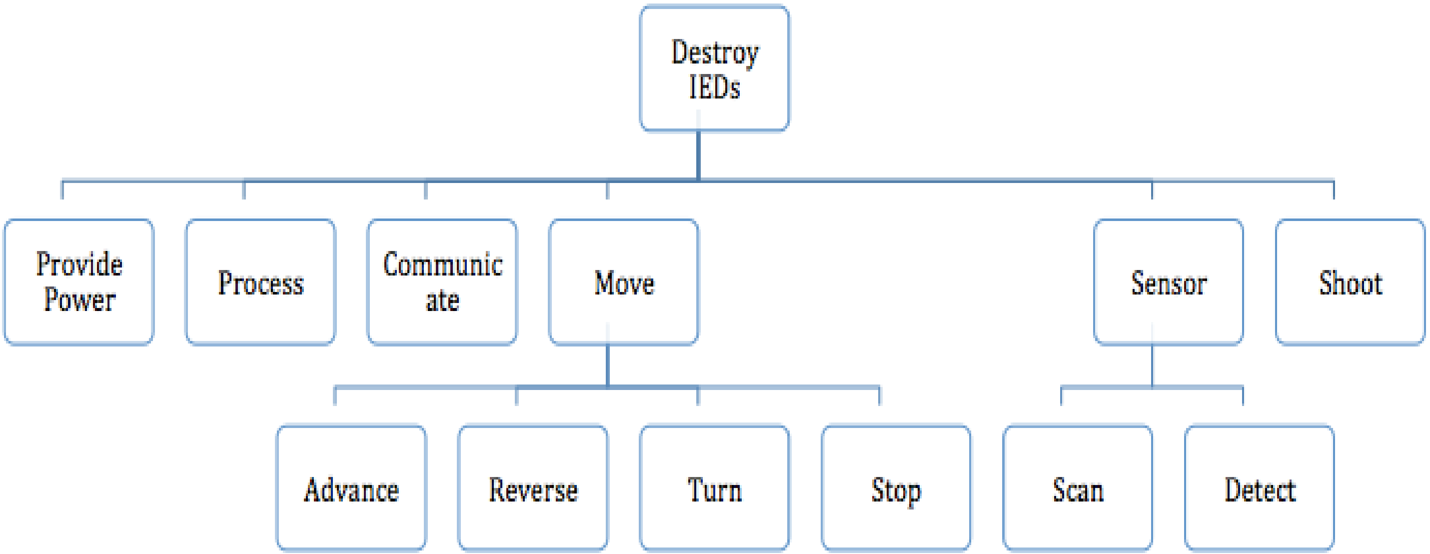

Figure 3. Functional Decomposition of IED Robot

The following section (Section 1) discusses the mapping of IED robot's functions to its elements that carry out the functions.

1. Network Elements

Based on the functional decomposition of the IED robot (Figure 3), to fulfill all the functions required of it, the IED robot needs six elements: a power system, a processor, a communication system, a motion system, a sensor and a shooter. The six elements, with their respective assigned element numbers, are indicated in Table 3:

Table 3. Elements of IED Robot

Element Number	Name
1	Power System
2	Processor
3	Communication System
4	Motion System
5	Sensor
6	Shooter

The mapping of the functions identified for the IED robot to its respective elements is depicted in Table 4.

Table 4. Mapping of Functions to Elements of IED Robot

		Elements					
		Power System	Processor	Communication System	Motion System	Sensor	Shooter
Functions	Provide Power	▯					
	Process		▯				
	Communicate			▯			
	Advance				▯		
	Reverse				▯		
	Turn				▯		
	Stop				▯		
	Scan for IED					▯	
	Detect IED					▯	
	Shoot IED						▯

2. Network Links

Figure 4 shows the IED robot represented as a network. The six elements (i.e., nodes) and the interfaces (i.e., links) between the elements of the system are indicated by the circles and the arrows, respectively. The interfaces allow for communication and interoperability among the elements of the system. The IED robot integration glues the six elements together so that they interface with each other to perform all the system functions. The interfaces are described briefly as follows.

The power system supplies power to all the other five elements. The processor acts as the 'brain' of the IED robot: it processes received feedback from the motion system, the sensor, and the shooter, and forms commands to these elements. All

commands and feedbacks in the system are sent via the communication system. Upon receiving the commands from the communication system, the motion system, the sensor, and the shooter execute the commands accordingly. The motion system maneuvers the IED robot, while the sensor scans for targets. Once the sensor detects a target, upon receiving the detection command from the processor, the shooter launches an interceptor to destroy the target.

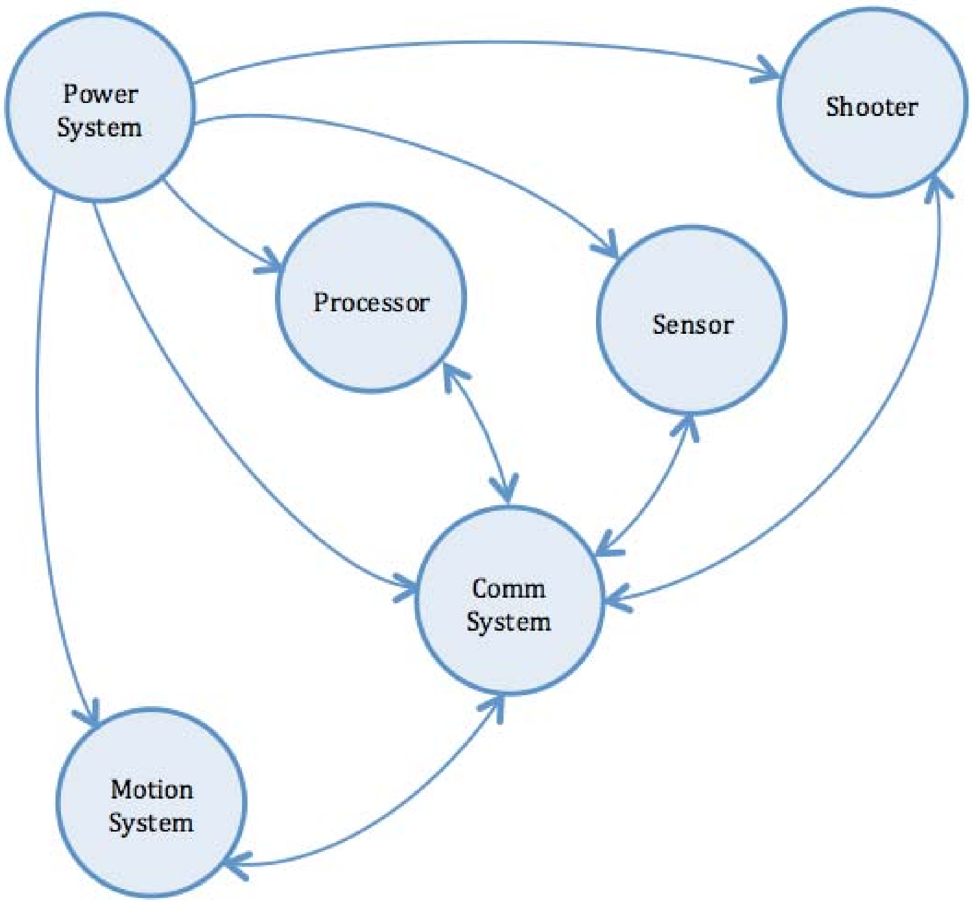

Figure 4. Network Representation of IED Robot

As mentioned in Chapter III, if a system has N nodes, the maximum possible number of links is $\frac{N(N-1)}{2}$, which is achieved only when all elements of the system interface with each other. For a system with six nodes, the maximum possible number of

links is 15. In the IED robot, as shown in Figure 4, not all of the system elements interface with each other. Hence, the number of links in the IED robot is less than 15. The total number of links in the IED robot is nine. The interfaces of the six elements in the IED robot are indicated by '✓' in Table 5:

Table 5. Interfaces of IED Robot

Elements	Power System	Processor	Communication System	Motion System	Sensor	Shooter
Power System		✓	✓	✓	✓	✓
Processor	✓		✓			
Communication System	✓	✓		✓	✓	✓
Motion System	✓		✓			
Sensor	✓		✓			
Shooter	✓		✓			

B. USE OF NETWORK ENTROPY IN ASSESSMENT OF IED ROBOT INTEGRATION SUCCESS

This section describes the computation of network entropy of the IED robot and its use in assessing the integration success of the robot.

1. Calculation of Network Entropy

With reference to (1), in the IED robot case, the total number of links in the network is nine, i.e., $L = 9$, and the number of possible states of each link is nine, i.e., $M = 9$.

a. *Link Numbering*

Table 6 captures the numbering of the links. As explained in Chapter III, the link connecting elements i and j is assigned a number as shown in Table 6. For example, $l = 2$ (i.e., Link 2) corresponds to (1, 2), which connects Element 1 (power system) and Element 3 (communication system).

Table 6. Link Numbering

Link, l	**Element Pair (i, j)**	**Element (i)**	**Element (j)**
1	(1, 2)	Power System (1)	Processor (2)
2	(1, 3)	Power System (1)	Communication System (3)
3	(1, 4)	Power System (1)	Motion System (4)
4	(1, 5)	Power System (1)	Sensor (5)
5	(1, 6)	Power System (1)	Shooter (6)
6	(2, 3)	Processor (2)	Communication System (3)
7	(3, 4)	Communication System (3)	Motion System (4)
8	(3, 5)	Communication System (3)	Sensor (5)
9	(3, 6)	Communication System (3)	Shooter (6)

b. *Link State Categorization*

The values of X_{Low} and X_{Med} are selected to be 0.40 and 0.75, respectively. Hence, as shown in Table 7, the three successful element development states of the IED robot are: "Low" if $0 \le p_D < 0.40$, "Medium" if $0.40 \le p_D < 0.75$, and "High" if $0.75 \le p_D \le 1$. The development of all the elements in the IED robot is assumed to fall in the same state categorization.

Table 7. Successful IED Robot Element Development States and Probabilities

Element Development State	**Probability of Successful Development,** p_D
Low (L_{ow})	$0 \le p_D < 0.40$
Medium (M_{ed})	$0.40 \le p_D < 0.75$
High (H_{igh})	$0.75 \le p_D \le 1$

Table 8 shows the nine different possible states for each link in the IED robot network.

Table 8. IED Robot Link States Assignment

		Element j		
		State L_{ow} ($0 \le p_D < 0.40$)	State M_{ed} ($0.40 \le p_D < 0.75$)	State H_{igh} ($0.75 \le p_D \le 1$)
Element i	State L_{ow} ($0 \le p_D < 0.40$)	State 1	State 2	State 3
	State M_{ed} ($0.40 \le p_D < 0.75$)	State 4	State 5	State 6
	State H_{igh} ($0.75 \le p_D \le 1$)	State 7	State 8	State 9

c. p_{lk} Determination

The assessment of systems integration requires the determination of both the probability of successful development of the system elements and the probability of successfully integrating the elements.

(i) *Probability of successful element development*. The probabilities of successful development, p_{D_i} and p_{D_j}, of element i and element j are obtained by generating a uniformly distributed random number that falls within the range corresponding to an assumed state using the Oracle Crystal Ball (Oracle Crystal Ball n.d.) software. Link 2 (i.e., $l = 2$) that couples the power system (i.e., Element 1) and the communication system (i.e., Element 3) (refer to Table 6) is used as an example. The numbers obtained for these two elements are shown in Table 9.

Table 9. Probabilities of Successful Element Development of Power System and Communication System

	Probability of Successful Development of Power System, p_{D_1}	**Probability of Successful Development of Communication System, p_{D_3}**
State L_{ow} ($0 \le p_D < 0.40$)	0.27	0.03
State M_{ed} ($0.40 \le p_D < 0.75$)	0.44	0.65
State H_{igh} ($0.75 \le p_D \le 1$)	0.86	0.91

From Table 9, for example, the probabilities of successful development of the power system and the communication system that are in state M_{ed} are obtained as 0.44 and 0.65, respectively, using one simulation run in the Oracle Crystal Ball software.

(ii) *Probability of successful pairwise integration*. To obtain the probabilities of successful integration elements, i and j, $p_C(i, j)$ and $p_I(i, j)$ need to be determined.

(a) *Determination of* $p_C(i,j)$. As explained in Chapter III, $p_C(i,j)=\min(p_{D_i},p_{D_j})$. Using the data in Table 9, the probabilities of successfully connection of the power system and the communication system for the nine link states obtained from one simulation run is shown in Table 10.

Table 10. Probabilities of Successful Connectivity of Power System and Communication System

Link State	p_{D_1} **(Development State of Power System)**	p_{D_3} **(Development State of Communication System)**	**Probability of Successful Connection,** $\min(p_{D_1},p_{D_3})$
1	0.27 (L_{ow})	0.03 (L_{ow})	0.03
2	0.27 (L_{ow})	0.65 (M_{ed})	0.27
3	0.27 (L_{ow})	0.91 (H_{igh})	0.27
4	0.44 (M_{ed})	0.03 (L_{ow})	0.03
5	0.44 (M_{ed})	0.65 (M_{ed})	0.44
6	0.44 (M_{ed})	0.91 (H_{igh})	0.44
7	0.86 (H_{igh})	0.03 (L_{ow})	0.03
8	0.86 (H_{igh})	0.65 (M_{ed})	0.65
9	0.86 (H_{igh})	0.91 (H_{igh})	0.86

Monte Carlo simulations (100 runs) are carried out to generate the probabilities of successful element development for all elements, using the Oracle Crystal Ball software. The probabilities of successful connectivity of two elements are then computed for all connectivity states according to (5).

Table 11 displays, as an example, the probability of successful connectivity results for the nine connectivity states of the power system and the communication system.

Table 11. Probabilities of Successful Connectivity of Power System and Communication System for all Connectivity States

		Communication System		
		State L_{ow} $(0 \le p_D < 0.40)$	State M_{ed} $(0.40 \le p_D < 0.75)$	State H_{igh} $(0.75 \le p_D \le 1)$
Power System	State L_{ow} $(0 \le p_D < 0.40)$	0.19 (State 1)	0.19 (State 2)	0.19 (State 3)
	State M_{ed} $(0.40 \le p_D < 0.75)$	0.22 (State 4)	0.43 (State 5)	0.43 (State 6)
	State H_{igh} $(0.75 \le p_D \le 1)$	0.22 (State 7)	0.55 (State 8)	0.77 (State 9)

The results shown thus far are computed for one link (i.e., Link 2) of the IED robot only. The computation is done for all the links in the system and the results are shown in Table 12.

Table 12. Probabilities of Successful Connectivity for all Links in IED Robot

$p_C(i_k, j_k)$	**Link 1**	**Link 2**	**Link 3**	**Link 4**	**Link 5**	**Link 6**	**Link 7**	**Link 8**	**Link 9**
State 1	0.14	0.11	0.13	0.13	0.14	0.13	0.13	0.14	0.12
State 2	0.20	0.19	0.18	0.20	0.21	0.20	0.20	0.19	0.18
State 3	0.20	0.19	0.18	0.20	0.21	0.20	0.20	0.19	0.18
State 4	0.21	0.18	0.21	0.19	0.19	0.20	0.20	0.23	0.19
State 5	0.52	0.49	0.52	0.51	0.52	0.51	0.51	0.51	0.51
State 6	0.58	0.56	0.58	0.58	0.59	0.56	0.59	0.58	0.57
State 7	0.21	0.18	0.21	0.19	0.19	0.20	0.20	0.23	0.19
State 8	0.58	0.54	0.57	0.57	0.58	0.56	0.56	0.56	0.57
State 9	0.83	0.83	0.83	0.83	0.83	0.84	0.83	0.83	0.83

The values in each column, shown in Table 12, are normalized. After normalization, the numbers obtained are consolidated in Table 13.

Table 13. Normalized Probabilities of Successful Connectivity for all Links in IED Robot

Normalized $p_C(i_k, j_k)$	**Link 1**	**Link 2**	**Link 3**	**Link 4**	**Link 5**	**Link 6**	**Link 7**	**Link 8**	**Link 9**
State 1	0.040	0.034	0.038	0.038	0.040	0.038	0.038	0.040	0.036
State 2	0.058	0.058	0.053	0.059	0.061	0.059	0.058	0.055	0.054
State 3	0.058	0.058	0.053	0.059	0.061	0.059	0.058	0.055	0.054
State 4	0.061	0.055	0.062	0.056	0.055	0.059	0.058	0.066	0.057
State 5	0.150	0.150	0.152	0.150	0.150	0.150	0.149	0.147	0.153
State 6	0.167	0.171	0.170	0.171	0.171	0.165	0.173	0.168	0.171
State 7	0.061	0.055	0.062	0.056	0.055	0.059	0.058	0.066	0.057
State 8	0.167	0.165	0.167	0.168	0.168	0.165	0.164	0.162	0.171
State 9	0.239	0.254	0.243	0.244	0.240	0.247	0.243	0.240	0.249

(b) *Determination of* $p_I(i, j)$. As in the computation of $p_C(i, j)$, the Oracle Crystal Ball software is used to perform Monte Carlo simulations of 100 runs to generate the probabilities of successful element development for all elements. The probabilities of successful interoperability of two elements are then computed for all interoperability states according to (6).

Table 14 displays, as an example, the probability of successful interoperability results for nine interoperability states of the power system and the communication system.

Table 14. Probabilities of Successful Interoperability of Power System and Communication System for all Interoperability States

		Communication System		
		State L_{ow} ($0 \le p_D < 0.40$)	State M_{ed} ($0.40 \le p_D < 0.75$)	State H_{igh} ($0.75 \le p_D \le 1$)
Power System	State L_{ow} ($0 \le p_D < 0.40$)	0.22 (State 1)	0.39 (State 2)	0.39 (State 3)
	State M_{ed} ($0.40 \le p_D < 0.75$)	0.22 (State 4)	0.55 (State 5)	0.62 (State 6)
	State H_{igh} ($0.75 \le p_D \le 1$)	0.22 (State 7)	0.55 (State 8)	0.88 (State 9)

The computation of the probability of successful interoperability of two elements is repeated for all the links in the IED robot and the results are shown in Table 15.

Table 15. Probabilities of Successful Interoperability for all Links in IED Robot

$p_I(i_k, j_k)$	**Link 1**	**Link 2**	**Link 3**	**Link 4**	**Link 5**	**Link 6**	**Link 7**	**Link 8**	**Link 9**
State 1	0.12	0.15	0.13	0.14	0.13	0.13	0.12	0.15	0.13
State 2	0.18	0.20	0.19	0.19	0.19	0.20	0.19	0.20	0.20
State 3	0.18	0.20	0.19	0.19	0.19	0.20	0.19	0.20	0.20
State 4	0.18	0.22	0.22	0.21	0.19	0.2	0.18	0.22	0.19
State 5	0.53	0.51	0.53	0.51	0.5	0.51	0.53	0.51	0.51
State 6	0.59	0.57	0.57	0.57	0.55	0.57	0.59	0.57	0.56
State 7	0.18	0.22	0.22	0.21	0.19	0.20	0.18	0.22	0.19
State 8	0.57	0.57	0.59	0.57	0.58	0.58	0.57	0.57	0.57
State 9	0.82	0.84	0.83	0.83	0.83	0.83	0.83	0.83	0.83

Again, the values in each column, shown in Table 15, are normalized. After normalization, the results obtained are consolidated in Table 16.

Table 16. Normalized Probabilities of Successful Interoperability for all Links in IED Robot

Normalized $p_I(i_k, j_k)$	**Link 1**	**Link 2**	**Link 3**	**Link 4**	**Link 5**	**Link 6**	**Link 7**	**Link 8**	**Link 9**
State 1	0.036	0.043	0.037	0.041	0.039	0.038	0.036	0.043	0.038
State 2	0.054	0.057	0.055	0.056	0.057	0.058	0.056	0.058	0.059
State 3	0.054	0.057	0.055	0.056	0.057	0.058	0.056	0.058	0.059
State 4	0.054	0.063	0.063	0.061	0.057	0.058	0.053	0.063	0.056
State 5	0.158	0.147	0.153	0.149	0.149	0.149	0.157	0.147	0.151
State 6	0.176	0.164	0.164	0.167	0.164	0.167	0.175	0.164	0.166
State 7	0.054	0.063	0.063	0.061	0.057	0.058	0.053	0.063	0.056
State 8	0.170	0.164	0.170	0.167	0.173	0.170	0.169	0.164	0.169
State 9	0.245	0.241	0.239	0.243	0.248	0.243	0.246	0.239	0.246

(c) *Combining* $p_C(i,j)$ *and* $p_I(i,j)$. As established in Chapter III, the probability of successful integration of two elements of the system is the product of $p_C(i,j)$ and $p_I(i,j)$ for each link state. As mentioned in Chapter III, the condition $\sum_{k=1}^{N} p_{lk} = 1$ has to be fulfilled for network entropy calculation. Table 17, as an example, shows the results of normalized value of p_{lk} for all the link states and for the link between the power system and the communication system $(l = 2)$. The same results can also be obtained by taking the product of the un-normalized values of $p_C(i,j)$ and $p_I(i,j)$ and normalizing the values afterwards. The normalized p_{lk} results for the remaining links of the IED robot can be found in the appendix.

Table 17. Normalized p_{lk} of Power System and Communication System

$l=2$: **Integration of Power System and Communication System,** $(1,3)$				
Link State, k	Normalized $p_C(1,3)$	Normalized $p_I(1,3)$	$p_{2k}=p_k(1,3)$	Normalized p_{2k}
1	0.034	0.043	0.001	0.009
2	0.058	0.057	0.003	0.022
3	0.058	0.057	0.003	0.022
4	0.055	0.063	0.003	0.023
5	0.150	0.147	0.022	0.143
6	0.171	0.164	0.028	0.183
7	0.055	0.063	0.003	0.023
8	0.165	0.164	0.027	0.176
9	0.254	0.241	0.061	0.399

d. Network Entropy Determination

Using (1), based on the data consolidated, the network entropy for IED robot is computed to be 14.86.

2. Assessing IED Robot Integration Success

In this thesis, the progress of the overall systems integration of the IED robot is tracked quarterly. To demonstrate the evolution of the entropy of the network, different scenarios with varying states of element development and integration activities, which include desirable (i.e., improvements) and undesirable (i.e., failures), are assigned to the development and integration of the elements of the system in each quarter. These scenarios, for a timeframe of eight quarters, are shown in Table 18.

Table 18. Scenarios Defined for Two-Year IED Robot Integration Timeframe

Quarter	**Scenario**	**Affected Links**
Q1	Element 2 failed	1 and 6
Q2	Designs of Element 2 and Element 3 (in Link 2) improved	1, 2 and 6
Q3	Testing of Element 5 failed	4 and 8
Q4	Testing of Element 5, Element 3 (in Link 7) and Element 4 (in Link 7) improved	4, 7 and 8
Q5	Testing of Element 4 (in Link 3) improved	3
Q6	Testing of Links 5 and 6 improved	5 and 6
Q7	Testing of Links 8 and 9 improved	8 and 9
Q8	Testing of Link 9 improved	9

a. Desirable Scenarios

For scenarios in which there are desirable changes made to the element development, the transition matrix of a Markov chain, P, as defined in Chapter III, is applied to calculate the new values of X_{Low} and X_{Med}, after a transition period, for the affected element.

In this thesis, the transition matrix P is assumed to be fixed during the integration timeframe and is given by $P = \begin{pmatrix} 0.3 & 0.7 & 0 \\ 0 & 0.4 & 0.6 \\ 0 & 0 & 1 \end{pmatrix}$. The transition probabilities, π_{xy}, are thus fixed during the integration timeframe.

In the Q2 scenario, given $x(t) = \begin{pmatrix} 0.4 & 0.75 & 1 \end{pmatrix}^T$ defined in Chapter IV and P, it follows from (9) in Chapter III that $X_{Low} = 0.65$ and $X_{Med} = 0.9$ at $(t + \delta t)$.

These values, X_{Low} and X_{Med}, at $(t + \delta t)$ are used to generate the probabilities of successful development of Element 2 at different development states, which are later used to calculate the network entropy of the system.

b. Undesirable Scenarios

For scenarios in which undesirable changes occurred to the development of the element, such as the scenarios defined in Q1 and Q3, the values of X_{Low} and X_{Med} are decreased. In this thesis, the values of X_{Low} and X_{Med} at $(t + \delta t)$ are arbitrarily set at 0.2 and 0.6, and 0.3 and 0.65 for Element 2 and Element 5, respectively.

Based on the scenarios given in Table 18, the computed network entropy for each quarter is shown in Table 19.

Table 19. Computed Network Entropy for each Integration Quarter

Quarter	**Network Entropy**
Q1	14.57
Q2	15.14
Q3	15.01
Q4	15.40
Q5	15.46
Q6	15.67
Q7	16.01
Q8	16.09

Figure 5 shows the tracking of the corresponding quarterly network entropy. The tracking indicates that as the design and integration activities fail, the network entropy decreases, and, as they improve, the network entropy increases. In Q3, for example, the testing of Element 5 fails, which results in a decrease in network entropy at the end of Q3, as shown in Figure 5. Once this problem is solved, and together with other improvements, the network entropy increases again. These results are in line with the results obtained in Huynh (2011).

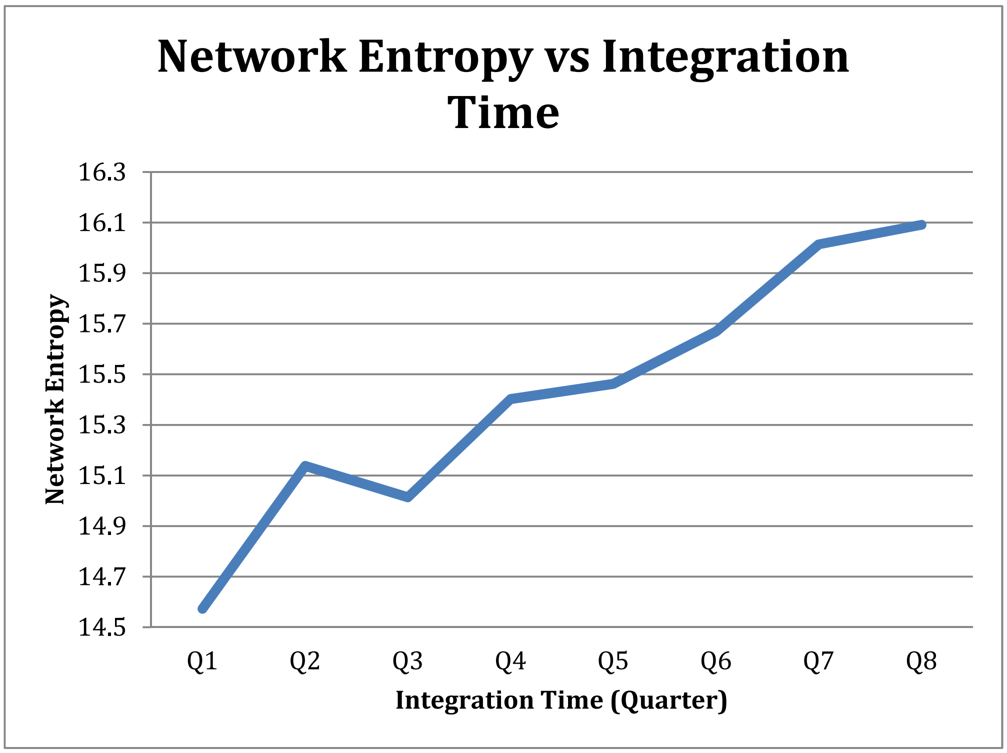

Figure 5. Network Entropy with Integration Time

V. CONCLUSION AND RECOMMENDATIONS

This chapter summarizes the results and the conclusions drawn from this research. Future work in this research area is also recommended.

A. RESEARCH SUMMARY

This research is inspired by the work in Huynh (2011) on an entropic approach to systems integration assessment and aims to extend Huynh's work by considering more than two possible states for each link connecting two elements to be integrated in the system. The extension of the work involves probabilistic modeling, simulation, and the use of an IED robot for illustration.

1. Probabilistic Modeling

For a system to be successfully integrated, its elements must achieve successful connectivity and interoperability. Successful system integration is related to development and integration activities. The successes of these activities are by no means certain, and, hence, the development and integration activities are ascribed probability distributions.

a. Development Activities

The development of each element of the system is assumed to fall in one of three development states. The probability of successful development of the element in each development state is ascribed a uniform distribution, which is obtained by generating a uniformly distributed random number that falls within the range corresponding to the assumed state.

The state of the link between two elements being integrated depends on the development states of the elements. Since there are three different development states for each element, there are nine possible states for each link.

b. Integration Activities

The probability of successful integration of a pair of elements is related to the probabilities of successfully connecting the two elements, and testing the connection and interoperability of the elements. The probabilities of successful connectivity and successful interoperability of two elements are both assumed to be related to the probabilities of successful development activities. These probabilities are unlikely to exceed the probability of successful development of either element; it is, hence, taken to be the minimum of the probabilities of successful development of the two elements.

The event of establishing the connectivity testing and the event of passing the interoperability testing are assumed to be independent. With this assumption, the probability of successfully integrating two elements of the system is taken to be the product of the probability of successful connectivity of the two elements and the probability of successful interoperability of the two elements.

2. Simulation

The success of development activities cannot be assessed just by a single probability value. Hence, Monte Carlo simulations are required. In this thesis, the Monte Carlo simulations are carried out, using Oracle Crystal Ball software, to generate the probabilities of successful element development, which in turn are used to compute the probability of successful connectivity of two elements, as well as the probability of successful interoperability of two elements.

3. Illustration with IED Robot

An IED robot developed to engage improvised explosive devices is used in illustrating the proposed entropic approach to assessing the success of integrating a system. A two-year IED robot integration timeframe is assumed, and the states of element development and integration activities vary during each integration quarter. The IED robot is represented as a network, and the network entropy of the IED robot is computed for each integration quarter.

B. RESEARCH RESULTS

The quantitative results obtained from the simulations for the network entropy show that, as the design and integration activities fail, the network entropy decreases, and, as they improve, the network entropy increases. These results are in line with the results obtained in Huynh (2011).

C. CONCLUSION

The work in Huynh (2011) shows that the network entropy could be used as an aid to assess systems integration success. This is a significant finding as using entropic approach to assess systems integration could help system integrators to be aware of the systems integration effort needed in each integration phase so as to be better prepared if corrective actions need to be taken.

In this thesis, the work in Huynh (2011) is extended. More than two possible states for each link, as well as assigning probabilistic measures to the systems development and integration activities and capabilities to obtain the probabilities required to compute the network entropy of the system are considered. This thesis demonstrates how system links are assigned nine possible states and how probabilistic measures are ascribed to system design and integration activities and capabilities.

The results from this extended work, as demonstrated in the IED robot illustration, show that failures in design and integration activities would cause a decrease in the network entropy and, hence, failure in the IED robot integration, and improvements in the activities would result in an increase in the network entropy and, hence, success in the IED robot integration. The entropic approach is, thus, feasible for assessing systems integration success. Furthermore, this work demonstrates a successful extension of the work in Huynh (2011) to links in the network with more than two possible states.

D. RECOMMENDATIONS

The following studies/research are recommended for future work:

1. Usage of Real Data

In this thesis, the same probability of successful element development range is assumed for all the elements of the system. However, if real data of the probability of successful development is known for each element, the data should be used instead.

2. Consideration of More Development and Integration Activities

Systems integration involves many development and integration activities, such as design, build and test, considered in this thesis. The development and integration activities could be further broken down into specific activities, which are assigned different probabilistic measures. Dependency relationships among these activities are also defined.

3. Assignment of Different Link States

In this thesis, the same categorization of link states is assigned for the connectivity state and the interoperability state. It is not necessary that the link categorization be the same for connectivity state and the interoperability state. A different link state categorization could be explored for the connectivity state and the interoperability state.

APPENDIX

This appendix consists of the calculations of the probabilities of successfully integrating two elements of the system for the nine link states and the nine links in the IED Robot. The normalized p_{lk} results are shown in Tables 20 to 28.

Table 20. Normalized p_{lk} of Power System and Processor

$l=1$: **Integration of Power System and Processor,** $(1,2)$				
Link State, k	Normalized $p_C(1,2)$	Normalized $p_I(1,2)$	$p_{1k} = p_k(1,2)$	Normalized p_{1k}
1	0.040	0.036	0.001	0.009
2	0.058	0.054	0.003	0.020
3	0.058	0.054	0.003	0.020
4	0.061	0.054	0.003	0.021
5	0.150	0.158	0.024	0.154
6	0.167	0.176	0.029	0.191
7	0.061	0.054	0.003	0.021
8	0.167	0.170	0.028	0.184
9	0.239	0.245	0.059	0.380

Table 21. Normalized p_{lk} of Power System and Communication System

$l=2$ **: Integration of Power System and Communication System,** $(1,3)$				
Link State, k	Normalized $p_C(1,3)$	Normalized $p_I(1,3)$	$p_{2k} = p_k(1,3)$	Normalized p_{2k}
1	0.034	0.043	0.001	0.009
2	0.058	0.057	0.003	0.022
3	0.058	0.057	0.003	0.022
4	0.055	0.063	0.003	0.023
5	0.150	0.147	0.022	0.143
6	0.171	0.164	0.028	0.183
7	0.055	0.063	0.003	0.023
8	0.165	0.164	0.027	0.176
9	0.254	0.241	0.061	0.399

Table 22. Normalized p_{lk} of Power System and Motion System

$l = 3$: **Integration of Power System and Motion System,** $(1,4)$				
Link State, k	Normalized $p_C(1,4)$	Normalized $p_I(1,4)$	$p_{3k} = p_k(1,4)$	Normalized p_{3k}
1	0.038	0.037	0.001	0.009
2	0.053	0.055	0.003	0.019
3	0.053	0.055	0.003	0.019
4	0.062	0.063	0.004	0.026
5	0.152	0.153	0.023	0.152
6	0.170	0.164	0.028	0.183
7	0.062	0.063	0.004	0.026
8	0.167	0.170	0.028	0.186
9	0.243	0.239	0.058	0.381

Table 23. Normalized p_{lk} of Power System and Sensor

$l = 4$: **Integration of Power System and Sensor,** $(1,5)$				
Link State, k	Normalized $p_C(1,5)$	Normalized $p_I(1,5)$	$p_{4k} = p_k(1,5)$	Normalized p_{4k}
1	0.038	0.041	0.002	0.010
2	0.059	0.056	0.003	0.021
3	0.059	0.056	0.003	0.021
4	0.056	0.061	0.003	0.022
5	0.150	0.149	0.022	0.146
6	0.171	0.167	0.028	0.186
7	0.056	0.061	0.003	0.022
8	0.168	0.167	0.028	0.183
9	0.244	0.243	0.059	0.387

Table 24. Normalized p_{lk} of Power System and Shooter

$l=5$ **: Integration of Power System and Shooter,** $(1,6)$				
Link State, k	Normalized $p_C(1,6)$	Normalized $p_I(1,6)$	$p_{5k} = p_k(1,6)$	Normalized p_{5k}
1	0.040	0.039	0.002	0.010
2	0.061	0.057	0.003	0.022
3	0.061	0.057	0.003	0.022
4	0.055	0.057	0.003	0.020
5	0.150	0.149	0.022	0.146
6	0.171	0.164	0.028	0.182
7	0.055	0.057	0.003	0.020
8	0.168	0.173	0.029	0.189
9	0.240	0.248	0.059	0.387

Table 25. Normalized p_{lk} of Processor and Communication System

$l = 6$ **: Integration of Processor and Communication System,** $(2,3)$				
Link State, k	Normalized $p_C(2,3)$	Normalized $p_I(2,3)$	$p_{6k} = p_k(2,3)$	Normalized p_{6k}
1	0.038	0.038	0.001	0.010
2	0.059	0.058	0.003	0.022
3	0.059	0.058	0.003	0.022
4	0.059	0.058	0.003	0.022
5	0.150	0.149	0.022	0.146
6	0.165	0.167	0.027	0.180
7	0.059	0.058	0.003	0.022
8	0.165	0.170	0.028	0.183
9	0.247	0.243	0.060	0.392

Table 26. Normalized p_{lk} of Communication System and Motion System

$l = 7$: **Integration of Communication System and Motion System,** $(3,4)$				
Link State, k	Normalized $p_C(3,4)$	Normalized $p_I(3,4)$	$p_{7k} = p_k(3,4)$	Normalized p_{7k}
1	0.038	0.036	0.001	0.009
2	0.058	0.056	0.003	0.021
3	0.058	0.056	0.003	0.021
4	0.058	0.053	0.003	0.020
5	0.149	0.157	0.023	0.151
6	0.173	0.175	0.030	0.194
7	0.058	0.053	0.003	0.020
8	0.164	0.169	0.028	0.178
9	0.243	0.246	0.060	0.385

Table 27. Normalized p_{lk} of Communication System and Sensor

$l = 8$ **: Integration of Communication System and Sensor,** $(3,5)$				
Link State, k	Normalized $p_C(3,5)$	Normalized $p_I(3,5)$	$p_{8k} = p_k(3,5)$	Normalized p_{8k}
1	0.040	0.043	0.002	0.012
2	0.055	0.058	0.003	0.021
3	0.055	0.058	0.003	0.021
4	0.066	0.063	0.004	0.028
5	0.147	0.147	0.022	0.145
6	0.168	0.164	0.028	0.184
7	0.066	0.063	0.004	0.028
8	0.162	0.164	0.027	0.178
9	0.240	0.239	0.057	0.383

Table 28. Normalized p_{lk} of Communication System and Shooter

$l=9$ **: Integration of Communication System and Shooter,** $(3,6)$				
Link State, k	Normalized $p_C(3,6)$	Normalized $p_I(3,6)$	$p_{9k}=p_k(3,6)$	Normalized p_{9k}
1	0.036	0.038	0.001	0.009
2	0.054	0.059	0.003	0.021
3	0.054	0.059	0.003	0.021
4	0.057	0.056	0.003	0.021
5	0.153	0.151	0.023	0.148
6	0.171	0.166	0.028	0.182
7	0.057	0.056	0.003	0.021
8	0.171	0.169	0.029	0.185
9	0.249	0.246	0.061	0.393

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